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The Tectogenesis Stages of the Antarctic Shield: Review of Geochronological Data

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Abstract—A review of numerous isotopic–geochronological studies is given. The major attention is paid to modern U–Pb zircon measurements using the SHRIMP method. The major tectogenesis stages recognized in the Antarctic shield are Archean (3800–3300, 3100–2800, and 2550–2450 Ma), Paleoproterozoic (2200–2000 and 1850–1700 Ma), Mesoproterozoic (1400–1250 and 1200–920 Ma), and Neoproterozoic–Early Paleozoic (600–500 Ma). Ancient Eo- and Paleoarchean processes (intrusion of tonalite gneisses protoliths, or metamorphism) took place at Enderby Land, Kemp Land, and the Prince Charles Mountains. At some localities tectonic activity ended at 1700 Ma, at other places reworking or rejuvenation occurred later. Mesoproterozoic tectogenesis was not synchronous. The completion phases of tectonic activity are known to have occurred in different places 1150, 1050, and 980–920 Ma ago. In areas of Mesoproterozoic tectogenesis, evidence of Paleoproterozoic or (rarely) Archean endogene processes is sometimes found. Most likely, this stage refers to the formation of the vast continental block. The Neoproterozoic–Early Paleozoic tectogenesis was practically synchronous over most of the Antarctic shield; on large areas it was characterized by metamorphism and pervasive schistosity, but in many other localities only various granitoids and pegmatites were intruded. Within all the areas of Neoproterozoic–Early Paleozoic tectogenesis isotopic evidence of the earlier (largely Mesoproterozoic) endogene processes are found.

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INTRODUCTION

Eastern Antarctica is a Precambrian craton [5] mainly underlain by crystalline basement rocks and is therefore referred to as ancient shield. The latter consists of several Archean or Archean–Paleoproterozoic protocraton blocks [2, 25] and a vast Late Proterozoic mobile belt of polycyclic development (2500–500 Ma) [24]. The Antarctic shield is made of various lithologic–structural complexes of metamorphic and magmatic rocks, almost without stratified sedimentary deposits. In this situation, isotope age determinations remain the major method of understanding the chronology of rock formation and development. During the last 10–15 years, foreign and Russian specialists have performed numerous Sm–Nd and U–Pb isotope-geochronologic studies. Reviews of isotope–geochronologic data of the Archean and Early Paleozoic (Pan-African) rocks and tectonic events are given in [11, 15]. However, the Proterozoic endogene processes dated over the entire continent have not been generalized. This paper is intended to fill this gap: the literature data are generalized and the author's unpublished personal data are considered. All the results were obtained by zircon SHRIMP dating, unless otherwise indicated. Some important data on the Sm–Nd isotope composition of rocks and isotope age estimations are also given. Geochronological data are arranged in large age intervals to allow characterization of each tectogenesis stage in relation to the whole Antarctic shield. Materials relevant to each of the stages are presented separately for different areas of eastern Antarctica from west to east (clockwise along the coast). As a rule, the separated areas are characteristic of specific geological structures and may be considered as independent terrains. Geological descriptions of certain areas were presented in [1, 2, 36].

ARCHEAN–EARLY PALEOPROTEROZOIC

Evidences of Archean (in some areas Neoarchean–Paleoproterozoic) endogene processes are found on certain localities of Antarctic shield, but on rather limited territory (Fig. 1).

Granites dated in a range of 3000–2800 Ma occur in the western part of Queen Maud Land, within Grunehogna terrain (Fig. 1) suggesting the formation of crust at this time. However, model Sm–Nd ages (DMT) of approximately 3200 Ma obtained from granite-gneisses xenoliths in Vestfjella basalts (data by Luttinen and Furnes, 2000) attest to earlier crust formation.

Russian workers dated tonalite orthogneisses of the Napier Complex of Enderby Land (Napier province) at about 4000 Ma (U–Pb–Th method [6]), this was confirmed by the data from foreign colleagues (3930 ± 30 Ma) [9]. In the same rocks two other endogene events are known: at about 2950 Ma (granulite facies metamorphism) and at 2480 Ma (plastic deformations and heating) [9]. However, later dating of the same zircon grains from the oldest population gave an age of

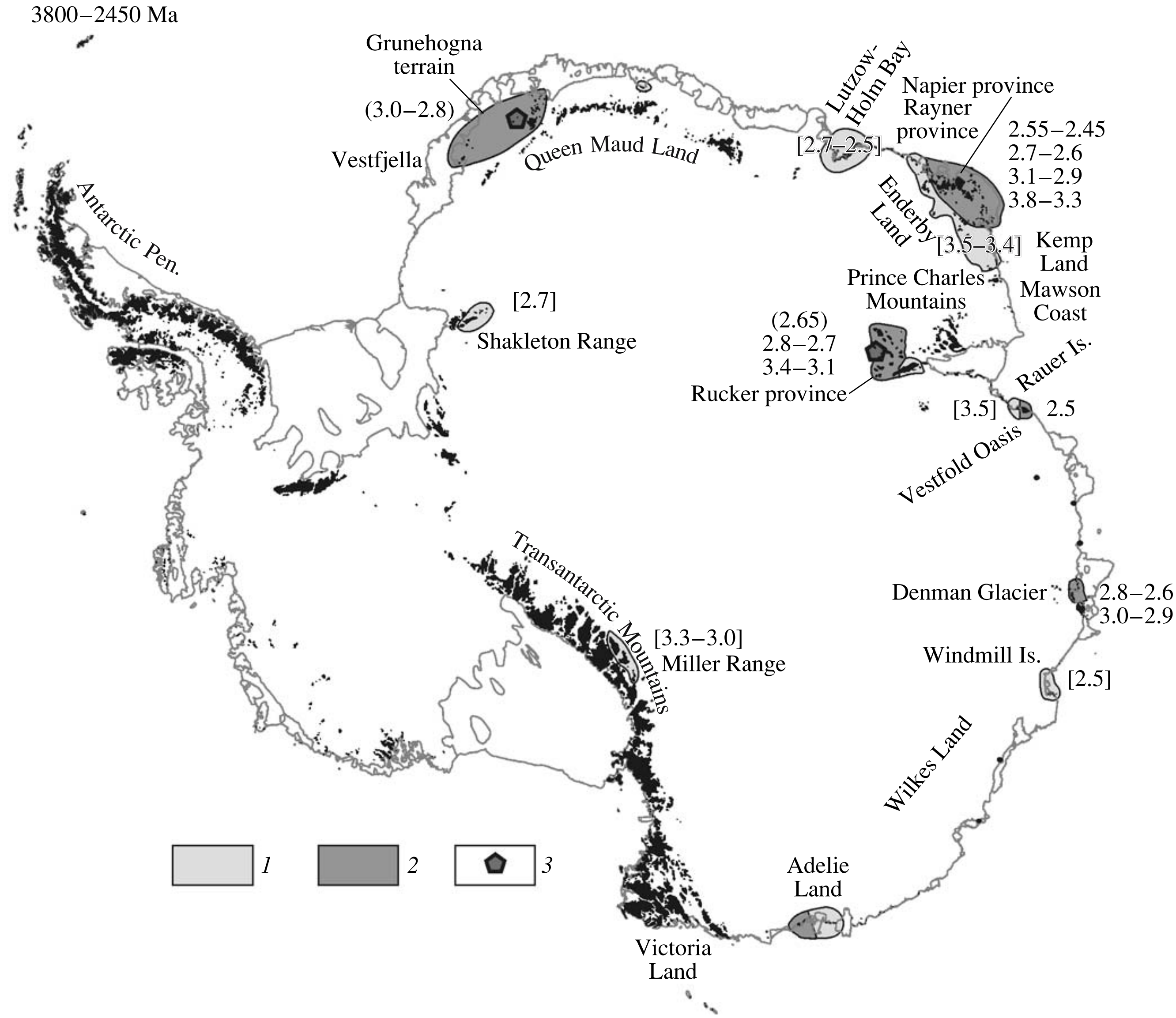

Fig. 1. Manifestations of the Archean endogene processes: *1*—distribution area of variously aged rocks with Archean isotopic tags (model Sm–Nd datings, zircon relict material); *2*—Archean metamorphic complexes weakly reworked or non-reworked by later processes; *3*—Archean post-tectonic granites and pegmatites. Figures on the sketch-map show major stages of endogene activity based on U–Pb data: in square brackets—datings of zircon inherited material; in parenthesis—datings of post-tectonic magmatic bodies; without brackets—datings of deep metamorphism and/or intrusion of granite-gneisses protoliths, usually syntectonic

3800 ± 50–100 Ma [20]. Other workers showed the age of the intrusion of a magmatic protolith of tonalite orthogneisses at about 3270 or 3070 Ma [22] and the age of granite–gneisses at the other localities to be 2700–2600 Ma [7, 14]. The age of high-temperature metamorphism (>1000°C) of the Napier Complex was determined to be in the range from 2480–2450 Ma [33].

Similar dating was obtained for syn-metamorphic pegmatite with an ultrahigh-temperature mineral association by L. Black (1983) using the "classical" zircon U–Pb method[1] Model Sm–Nd ages (DMT) of the rocks of this complex lie within 3900–3800 Ma (data by De Paolo, et al., 1982) suggesting the interpretation of this boundary as the time of primary continental protocrust formation. Rocks of the Napier Complex underwent metamorphism and plastic deformations within 3100–2800 Ma (classical U–Pb method [8, 9]; U–Pb SHRIMP method [20]). Recent studies of zircon and garnet by the SHRIMP method have provided grounds to believe an older age of ultrahigh-temperature metamorphism in the interval of 2590–2550 Ma (S. Harley, unpublished data). At the west of Enderby Land (in Rayner province and in Lutzow-Holm Bay) inherited zirconic material was dated at 2.7–2.5 Ga [35].

[1] This is the U–Pb method on hetero-granular zircon fractions using thermoionic mass-spectrometry.

For the Kemp Land (Fig. 1) the early stages of metamorphism at 3400, 2750, and 2450 Ma have been found in the Mesoproterozoic Rayner Complex [18]. Felsic orthogneisses on one locality of the Kemp Land are dated at 2692 ± 48 Ma (data by G. Clark, 1988). It should be noted that inherited zirconic material at Kemp Land is about 3100 Ma old. An Archean age of crust protoliths on this area has been confirmed by Hf isotopic studies that give values of model age (DMTHf) in an interval of 3600–3500 Ma [18].

Within Rucker province [2] in Prince Charles Mountains (Fig. 1) the oldest rock crystallized approximately 3390 Ma ago [31]. This granitic rock is the oldest rock in Antarctica that didn't undergo superimposed metamorphism and preserved its primary structure and texture. In the same area protoliths of plagiogneisses intruded at 3377 ± 9 Ma ago [31]. Protoliths of granite-gneisses intruded in the interval of 3185–3155 Ma ([13] and Author's unpublished data). In addition, Early Archean processes are shown by model Sm–Nd ages (DMT), primarily within the period of 3400–3200 Ma. Thermotectonic overprinting of rocks took place at 2790–2770 Ma [13]; these authors also showed the age of a pegmatite vein to be 2650 Ma.

The isotope ages of geological boundaries from Rauer Islands (Fig. 1) are comparable to those from Ruker province. According to P. Kinni (1993), protoliths of granite orthogneisses crystallized 3270 and 2800–2810 Ma ago. The zircon relict material is dated at 3.5 Ga [20].

The Vestfold Oasis area is largely composed of felsic orthogneisses which intruded and underwent plastic deformations and double metamorphism of granulite facies during a very short period of 50 Ma (from 2526 ± 6 to 2486 ± 6 Ma).

Tonalite-gneisses in the Denman Glacier area (Fig. 1) contain zircon populations attesting to rock crystallization about 3000 Ma ago and subsequent granulite metamorphism about 2890 Ma ago [11]. At another locality, a tonalite–gneiss protolith intruded 2640 ± 15 Ma ago [34]. Model Sm–Nd ages (DMT) of rocks in the Denman Glacier area are found largely within 2.3–1.9 Ga.

Inherited zirconic material dated at 2500 Ma was found in gneisses at the Windmill Islands and dated at 2800–2600 Ma, in migmatites on Adelie Land.

Layered gneisses at the Miller Range (Fig. 1) contain zircon with magmatic nuclei 3300–3050 or 3150–2980 Ma [17] and metamorphic rims 1720 and 530 Ma old.

At the Shackleton Range (Fig. 1) deeply metamorphosed strata of sedimentary or plutonic origin tectonically alternate with the Neoproterozoic sedimentary series. Granite orthogneisses have been dated by the isochrone Rb–Sr method at 2700 ± 100 Ma (Sri = 0.700 ± 4, after [36]; model Sm–Nd ages (DMT) of these rocks are in the interval of 3.2–2.3 Ga [38].

PALEOPROTEROZOIC

Evidences of the Paleoproterozoic tectonic and thermal processes are distributed irregularly. In most areas they are weakly expressed as relicts of ancient material in zircons of the younger rocks (granitoids or granite-gneisses) or as model Sm–Nd datings (DMT), but in some localities intrusion of pre- and syntectonic granitoids or leucosome-forming is dated as Paleoproterozoic. Mantle rocks of this age are practically unknown in Antarctica, with the exception of dykes of siliceous high-magnesium gabbronorite-dolerites or high-iron dolerites in the Napier province of Enderby Land, in Vestfold Oasis and possibly in the Rucker province in the Prince Charles Mountains (Fig. 2). These rocks are dated at 2350 Ma at Enderby Land, and 2241 ± 4, 2238 ± 7 or 1754 ± 16 Ma in the Vestfold Oasis ([26]; the last date refers to high-iron dolerites only).

Evidence of Paleoproterozoic inherited zirconic material (usually, from singular concordant analysis or, rarely, upper intersection of concordia) has been found in several areas (Fig. 2): ~2000 Ma at the west of Queen Maud Land and in Schirmacher Oasis, 2400–2200 Ma at the west of Enderby Land, 2400–2000 Ma at Kemp Land and at Mac Robertson Land, 1800 Ma at the Prydz Bay shore, and 2500–1700 Ma at the Windmill Islands [10, 32, 35].

Rocks of the Lambert terrain in the Prince Charles Mountains are dated in the interval from 2400 to 1700 Ma [31]. Protoliths of orthogneisses intruded at 2423 ± 18 Ma (based on the upper intersection of regression lines with concordia). U–Pb isotope analyses of zircon from augen gneisses are almost concordant and form a cluster with a weighted average age value of 2065 ± 23 Ma (based on $^{207}Pb/^{206}Pb$ ratio). This is interpreted as the age of metamorphism. Deformed vein material includes inherited zircon dated at about 2200 Ma. Zircon from mafic granulites of the Lambert terrain is dated at about 2150 Ma (supposedly a magmatic protolith) or about 2000 Ma (metamorphism?) (A. Korvino, personal communication). Weakly deformed felsic vein material contains a zircon population dated at about 1740 Ma using concordant analysis. Some samples of orthogneisses or non-deformed granitoids possess inherited zircon grains dated at 2200–2000 Ma ([13] and the author's unpublished data)

In Bunger Oasis (Fig. 2) granite-gneisses intruded at 1750 ± 15 Ma [34].

Based on well coordinated K–Ar, Rb–Sr, and U–Pb isotope data, a granite and pegmatite intrusion and amphibolite facies metamorphism took place on the Adelie Land area in the interval from 1800 to 1600 Ma. This metamorphism is dated at 1720–1680 Ma by the

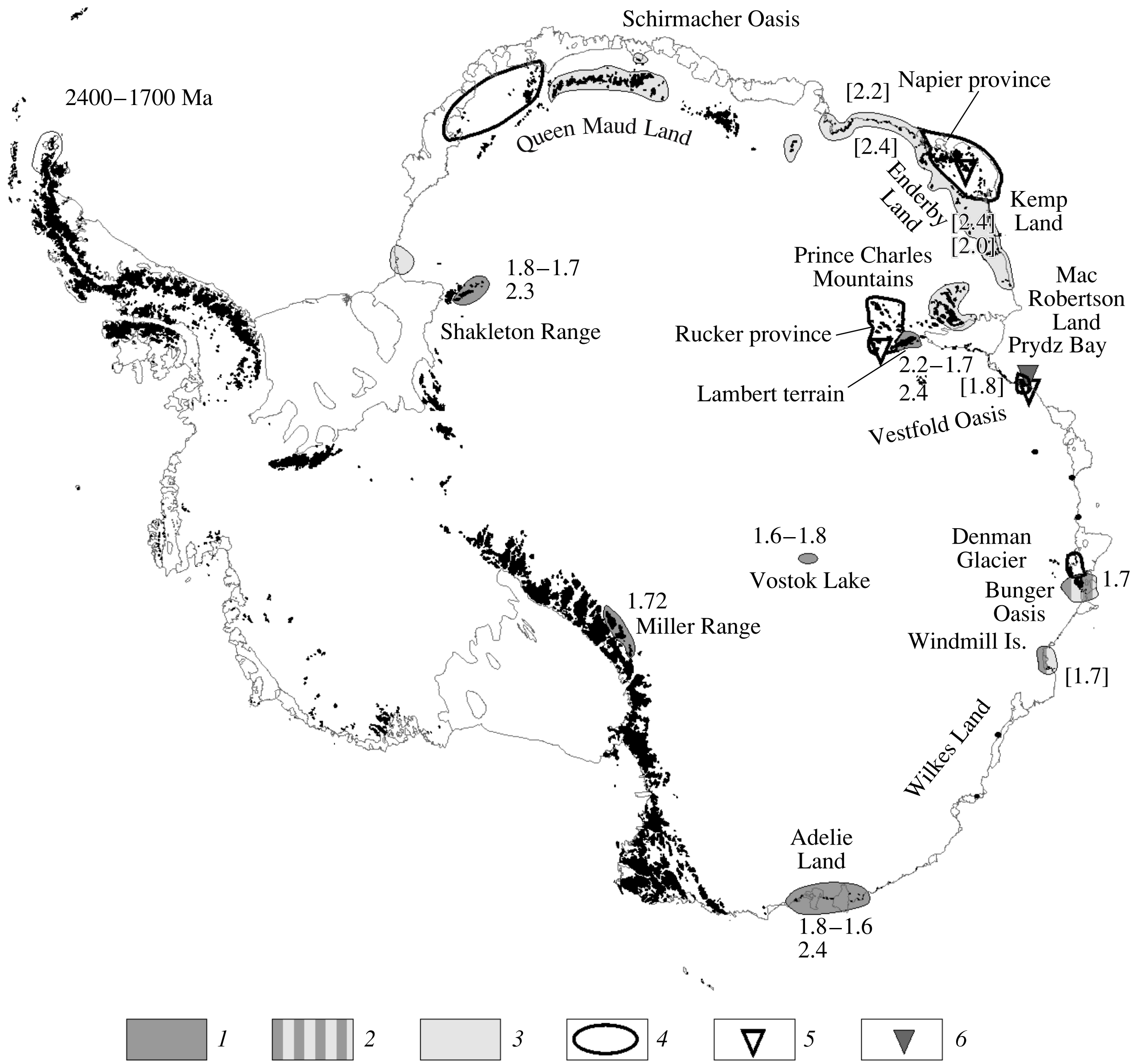

Fig. 2. Manifestation of the Paleoproterozoic endogene processes: *1*—distribution area of the Paleoproterozoic metamorphic complexes or granite-gneisses (2400, 2200–2150, 1850–1700 Ma); *2*—distribution area of the Paleoproterozoic rocks reworked in Mesoproterozoic (based on relict zircon U–Pb data); *3*—distribution area of rocks with the Paleoproterozoic model ages (DMT); *4* – distribution area of the Archean metamorphic complexes; *5*—swarms of dykes of siliceous high-magnesia gabbro-norite-dolerites (2400–2250 Ma); *6*—dykes of high-iron dolerite (1800 Ma). For figures on the sketch-map see Fig. 1

U–Pb isotope method on zircon and monazite, or at 1740 ± 140 Ma by the Rb–Sr method (Sri = 0.703) on vein material from migmatites [29]. However, some granitoid orthogneisses intruded at ~2400 Ma (based on intersection of regression lines with concordia).

The syntectonic granitoids in the Miller Range (Fig. 2) in the central part of Transantarctic Mountains intruded 1720 Ma ago [17].

In Shackleton Range protoliths of granite-gneisses intruded 2328 ± 47 and 1810 ± 2 Ma ago, while amphibolite facies metamorphism occurred 1715 ± 6 Ma ago (data by A. Brommer, et al., 1999; A. Ze, 1999).

Practically the same result (1740 ± 40 Ma) was obtained on zircons from the bedrock of Eastern Antarctic Ice Shield drilled on the Vostok Station [4].

The Paleoproterozoic model Sm–Nd (DMT) ages for crystalline rocks are found to predominate in almost all distribution areas of Mesoproterozoic and Neoproterozoic–Early Paleozoic metamorphic and plutonic rocks.

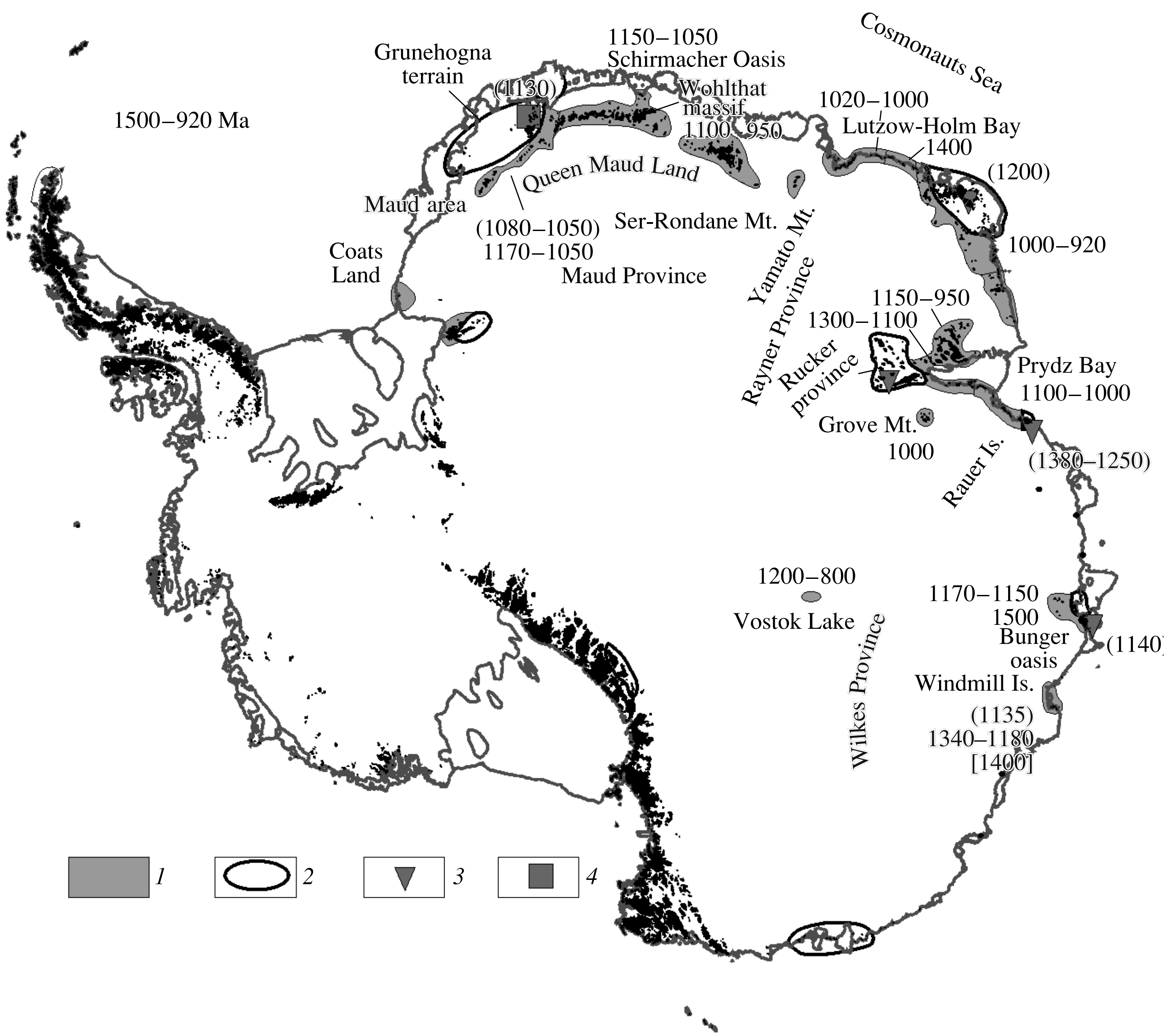

Fig. 3. Manifestation of the Mesoproterozoic endogene processes: *1*—distribution area of the Mesoproterozoic metamorphic and magmatic complexes; *2*—distribution area of the Archean or Paleoproterozoic geological complexes that did not undergo Mesoproterozoic processes; *3*—swarms of mafic dykes; *4*—basic rocks sills. For figures on the sketch-map see Fig. 1; datings of mafic complexes (dykes and sills) are italicized

MESOPROTEROZOIC–EARLY NEOPROTEROZOIC

Outcrops of these rocks are known in most of the area from Coats Land at the extreme west, to the Windmill Islands at the east (Fig. 3) in the first approximation corresponding to the Indian–Atlantic sector of the mainland. This vast area is underlain by metamorphic rocks of amphibolite and granulite faces, as well as various magmatic complexes [2, 36].

Non-deformed acid volcanics—granophyres and graphic granites, as well as microdiorite dykes dated at 1112 ± 4 Ma (data by V. Goze, 1997) are distributed over Coats Land.

At the west of Queen Maud Land (Fig. 3) in the Grunehogna terrain Mesoproterozoic sedimentary and volcanic rocks are 1130 Ma old (U–Pb measurements on zircons from volcanics); they emplace contemporaneous dolerite sills. Within the Maud province composed of metamorphic rocks and granites, the oldest (1170–1130 Ma) are magmatic protoliths of metamorphosed felsic and bimodal metavolcanics [12, 21, 24], and also tonalite orthogneisses (1150–1130 Ma). Metamorphism of granulite or amphibolite facies accompanied by intense plastic deformations is dated within the period of 1100–1035 Ma [12, 21, 24].

In the centre of the Queen Maud Land area (Wohlthat Massif Fig. 3) the oldest rocks are deeply metamorphosed bimodal volcanics intruded 1130 Ma ago [23]. Pre- and syntectonic orthogneisses intruded from 1150 to 1115 Ma ago; syntectonic granitoids intruded on a background of granulite facies metamorphism 1090–1050 Ma ago [23, 24]. Ages of about 1140–1150 Ma are estimated by the classical method (unpublished data of the author) on orthogneisses studied in the Schirmacher Oasis.

The complex structure and multiphase history are known for metamorphic rocks at the east of Queen Maud Land and in the western part of Enderby Land (Ser-Rondane Mountains, Yamato Mountains, and the coast of Lutzow-Holm Bay, Fig. 3.). In many places there is evidence of metamorphism within 1100–950 Ma, with much older magmatic protoliths. Thus, tonalite orthogneisses are dated at 1017 ± 13 Ma [35], granite-gneisses—1006 ± 21 Ma, and granulite facies metamorphic rocks about 1020 Ma (Rb–Sr method). Only one measurement by the classical method showed the age of an orthogneiss protolith intrusion at 1400 Ma [10]. Isotope evidence of endogene processes in the interval of 1300–900 Ma was obtained from zircons from Rayner Complex metamorphic rocks in the inland part of Enderby Land [35].

On Kemp Land, and Mac Robertson Land (Fig. 3) U–Pb dates correspond to geological processes taking place from 1650 to 920–910 Ma ago. Evidence of the oldest processes (as separate zircon populations) is found at the Kemp Land, where isotope data (DMT) attest to ancient (Archean) protoliths. The culmination of endogene processes (metamorphism and the accompanying intrusion of orthogneisses) took place at 1000–900 Ma. Late-tectonic plutons of charnockites and other granitoids intruded from 990 to 910 Ma, while multiple amphibolite–granulite facies metamorphism in some mylonite zones took place 930–900 Ma ago.

In the northern and central parts of Prince Charles Mountains (Beaver and Fisher provinces) [30] the earliest events of this stage, volcanic eruptions and intrusion of pre- or syntectonic granitoids, have been dated at 1300–1290 Ma ([30] and references in this paper). Granitoids intruded at 1220–1190 and 1120–1020 Ma; usually they are intensely deformed and only locally post-tectonic. Granulite facies metamorphism and intrusion of late-tectonic charnockites took place at 990–980 Ma, thermal impact and discrete tectonic zones developed at 950–940 Ma. A pluton of layered gabbro originated at 1290–1200 Ma; isotope overbalancing due to gabbroid metamorphism 1023 ± 33 Ma ago is observed ([30] and references in this paper).

In the southern part of Prince Charles Mountains (Rucker province and Lambert terrain) endogene processes are manifested weakly. In the Lambert terrain late-tectonic granitoid, veins intruded at 920 ± 10 Ma (unpublished data of the author).

On Rauer Islands (Fig. 3) granite, monzodiorite and leucogranite orthogneisses intruded at 1027 ± 27, 1000 ± 37, and 998 ± 18 Ma contemporaneously with metamorphism processes.

In Vestfold Oasis, as well as in Napier province of Enderby Land numerous mafic dykes are found. Their intrusion is dated using the U–Pb method on zircon and baddeleyite at 1380 ± 7, 1248 ± 4, and 1241 ± 5 Ma [26, and others]. In the Grove Mountains protoliths of orthogneisses intruded at 1000 ± 30 Ma.

In Bunger Oasis (Fig. 2) granodiorite orthogneisses crystallized about 1500 Ma ago; peak metamorphism conditions at 1190 ± 15 Ma ago were accompanied by intense plastic deformations [34]. Numerous plutonic, mainly felsic, rocks were intruded simultaneously with the closing stages of tectonic activity about 1170 and 1150 Ma ago [34].

At Windmill Island (Fig. 3), intrusion of felsic gneisses coincided in time with zonal metamorphism from amphibolite to granulite facies and plastic deformations at 1400–1300 Ma [32]. Multiple metamorphism and deformations also took place at 1210–1180 Ma, accompanied by charnockitoids intrusion. The active geological history of the area finished 1135 Ma ago with the intrusion of post-tectonic granitoids [32].

Concordant analyses of zircons from drilled bedrock of the Eastern Antarctic Ice Sheet on Vostok Station [4] suggest an age of rock crystallization from 1200 to 800 Ma.

MIDDLE NEOPROTEROZOIC

Neoproterozoic rocks and processes in the interval of 850–700 Ma are not widely found in the Eastern Antarctica. Magmatic rocks are presented by rare granitoids (predominantly post-tectonic) and mafic dykes (Fig. 4). Post-tectonic granitoids and pegmatites dated at 750–720 Ma are known among the Rayner Complex rocks (Enderby Land). Deformed granitoids (augen gneisses) in the central part of Queen Maud Land (Schirmacher Oasis) are dated as 710 ± 24 Ma (classical method, author's unpublished data). A thermal event occurring 760–680 Ma ago was detected by a Sm–Nb garnet isotope study. Non-deformed mafic dykes in Fisher terrain in Prince Charles Mountains are dated at 845 ± 66 Ma (Sm–Nd isochrone; unpublished material by A.A. Laiba).

LATE NEOPRONEROZOIC–EARLY PALEOZOIC

In the central and western parts of Queen Maud Land (Fig. 5) evidence of the Late Neoproterozoic–Cambrian processes is distributed irregularly. No thermal imprint is registered west of Heimefronfjella Range, where metamorphic rocks and pegmatites are dated at 990–960 Ma. This territory is separated by a

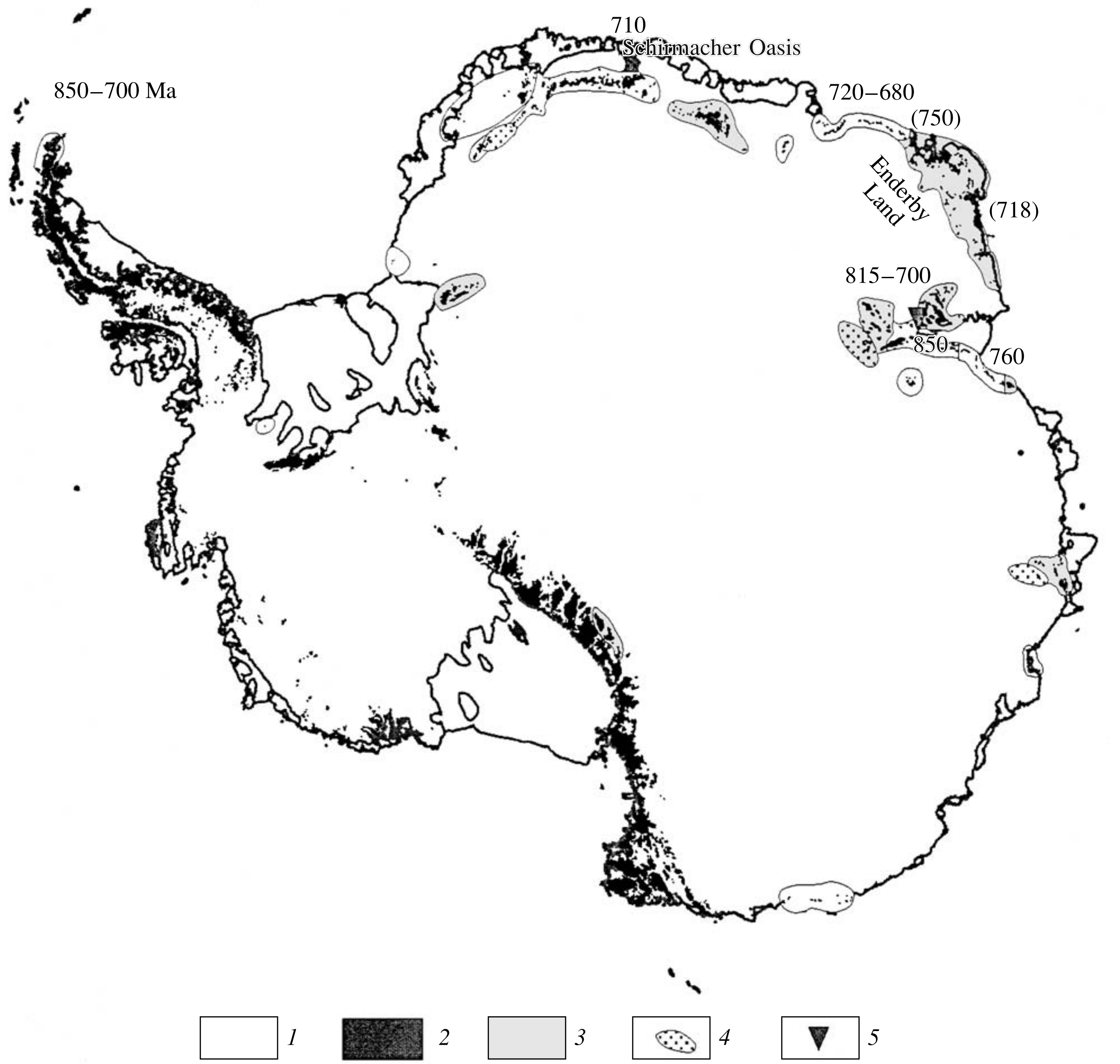

Fig. 4. Manifestation of the Neoproterozoic endogene processes: *1*—distribution area of the Precambrian rocks without Neoproterozoic thermal impact; *2*—distribution area of Neoproterozoic metamorphic complexes; *3*—area of thermal reworking of the Mesoproterozoic metamorphic complexes; *4*—the metamorphosed Neoproterozoic sedimentary complexes; *5*—dolerite dykes. For figures on the sketch-map see Fig. 1; datings of alkaline mafic rocks are italicized

thick northeast-trending zone of blastomilonites from areas with the intense Late Neoproterozoic–Cambrian processes. Amphibolite facies metamorphism with accompanying pervasive schistosity took place 540 Ma ago [12]. Rocks of the Wohlthat Massif in the central part of Queen Maud Land (felsic gneisses and mafic schists) have been dated by classical U–Pb and Sm–Nd isotope methods at 588 ± 4 and 570 ± 4 Ma. The latter are interpreted as plutonic activity and granulite facies regional metamorphism; intrusion of charnockites and anorthosite plutons is dated at 512 ± 2 and 506 ± 2 Ma correspondingly. These values were confirmed by the SHRIMP U–Pb method, which also revealed several stages of tectonic-and-magmatic activity in a range of 610–510 Ma [23]. Syn-tectonic granitoids (orthogneisses) with magmatic and metamorphic zircons have been dated at 530 Ma (on both populations of zircons [23]). The classical U–Pb age of the several hundred meters thick blastomylonite zone within the Wohlthat Massif is 529 ± 4.5 Ma (unpublished data of the author).

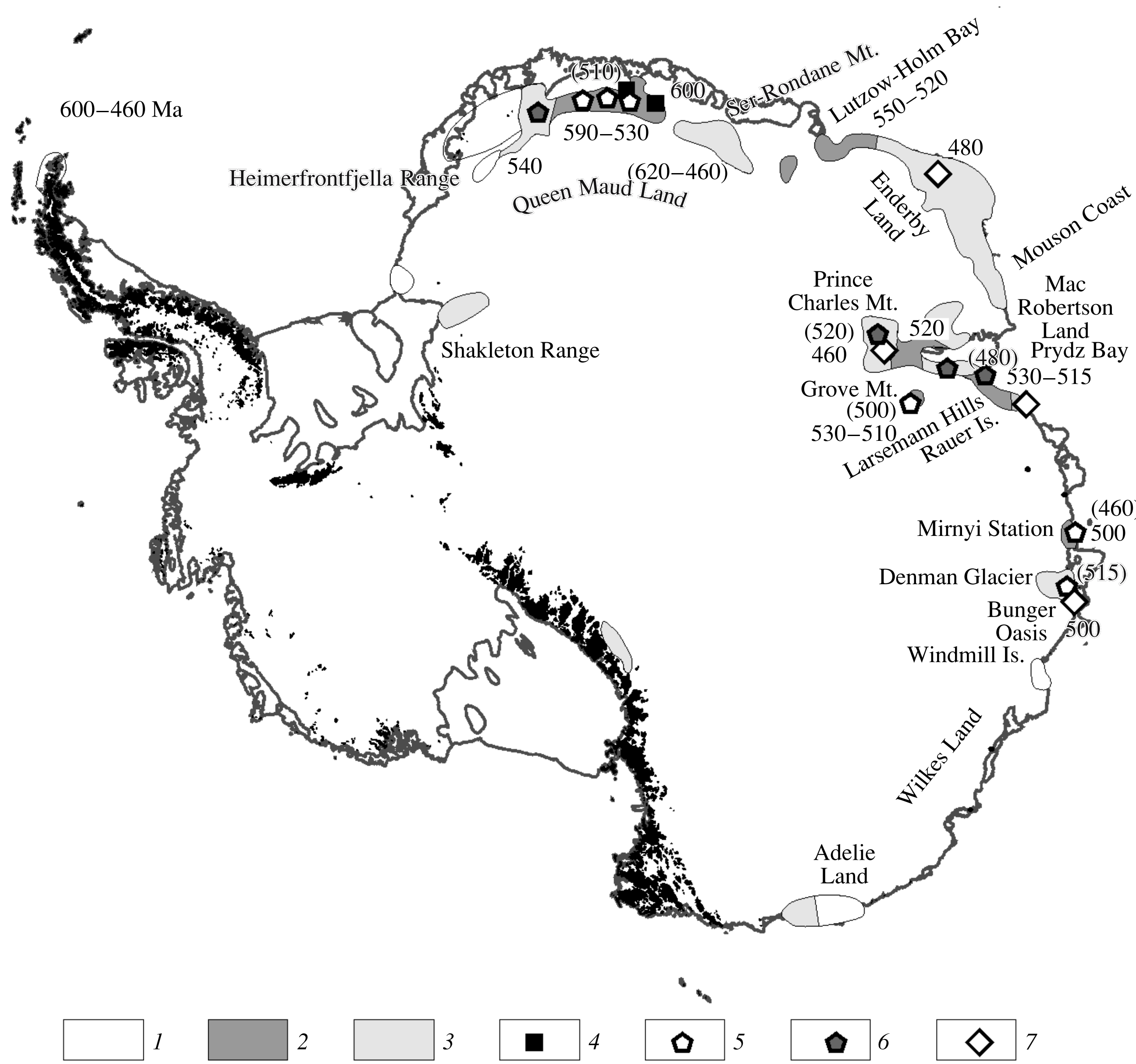

Fig. 5. Manifestation of the Late Neoproterozoic–Early Paleozoic endogene processes: *1*—distribution area of the Precambrian rocks not affected by thermal processes in Late Neoproterozoic–Early Paleozoic; *2*—distribution area of Late Neoproterozoic–Early Paleozoic (600–510 Ma) metamorphic complexes or intense tectonic-and-thermal reworking of Mesoproterozoic or Paleoproterozoic metamorphic complexes; *3*—the distribution area of the Precambrian metamorphic complexes experienced weak thermal impact (loss of lead in zircon, over balancing of Rb–Sr system, K–Ar datings); on some localities plastic deformations and intrusions of numerous pegmatites and leucogranites veins are observed; *4–7*—post-tectonic intrusive bodies: *4*—anorthosites, *5*—charnockitoids, *6*—granites, *7*—dykes of alkaline granites or lamprophyres. For figures on the sketch-map see Fig. 1; datings of alkaline mafic rocks are italicized

In the Ser-Rondane Mountains (Fig. 5) Late Proterozoic–Early Paleozoic events are expressed by amphibolite facies metamorphism and intrusion of numerous granitoids 620–460 Ma ago. Further east, in the area of Lutzow-Holm Bay, zonal metamorphic complexes occur. Isotope studies of zircon revealed tectonic and thermal processes 550–520 Ma previously (metamorphism and formation of pervasive schistosity); a gradual decrease in rock ages and increase of metamorphism degree are observed in the east–west direction [16, 33].

On Mac Robertson Land (including the Prince Charles Mountains), and at Princess Elizabeth Land, Late Neoproterozoic–Early Paleozoic rocks are distributed very irregularly. Post-tectonic granitoids form small stock-like plutons or vein systems (sometimes thick swarms) in the southern part of this area (in Rucker and Lambert provinces). In the northern part of Prince Charles Mountains (Fisher terrain) pre- or syntectonic granitoids are dated within 550–530 Ma. Amphibolite facies metamorphism in the local zone of plastic deformations in Lambert terrain took place at 553 ± 21 Ma. Post-tectonic granitoids (dykes or medium-sized plutons) at this location have been dated from 520 ± 5 (at the south of the territory) to 480 ± 2 Ma (at the north of the area).

The coast of Prydz Bay in the area of Larsemann Hills (Fig. 5), underlain by paragneisses and high-alumina crystalline schists, experienced repeated plastic deformations, polymetamorphism and granitoids intrusions. This is shown by dates of 514 ± 7, 556 ± 7–531 ± 8, interpreted as syntectonic intrusions of granite-gneisses [39]. Sm–Nd measurements in the system's garnet–bulk sample gave ages generally between 514–490 Ma. In the Archean orthogneisses and relatively young pegmatites on Rauer Islands a significant loss of lead and an increase in zircon content was shown at 500 Ma.

In the Grove Mountains (Fig. 5) metamorphism of granulite facies and syntectonic granitoids' intrusions took place about 530 or 510 Ma ago [27], and charnockites intruded at 504 ± 2 Ma (by the classical method).

In the area of Mirnyi Station a Cambrian age (504 ± 3 Ma) was defined for vein granites and an Ordovician (about 460 Ma) age was shown for charnockites (unpublished data of the author). The dated granitoids represent vein material of plagiogranite agmatites.

In the area of Denman Glacier and Bunger Oasis, Early Paleozoic processes are manifested in partial or complete overbalancing of mineral Rb–Sr and K–Ar systems with local greenschist metamorphism. Numerous granitoids plutons are found here, for example, a syenite pluton was shown to be 516 Ma old in [11]. In Bunger Oasis, dykes of mafic alkaline rocks intruded during this stage [34].

At some localities of the Shackleton Range (Fig. 5) the age of metamorphism is defined at 530–550 Ma (Sm–Nd, U-Pb monazite measurements; Rb–Sr and K–Ar determinations on minerals [38]).

CONCLUSIONS

The oldest Eo- and Paleoarchean (3300–3800 Ma) orogenic processes (intrusion of protoliths of tonalite gneisses or metamorphism) are observed at Enderby Land and Kemp Land, also in the Prince Charles Mountains. Yet, today we have only one granitoid sample dated at 3400 Ma (in the Rucker province of the Prince Charles Mountains) that didn't experience metamorphism and deformation. Usually, processes of this period are studied by isotope methods (on relict, inherited zircon or model Sm–Nd dating) in younger rocks. Mesoarchean (3100–2800 Ma) processes are known on a much larger area: the western part of Queen Maud Land, Enderby Land, Denman Glacier and the central part of Transatlantic Mountains (Miller Range). Pre- or syntectonic orthogneisses or metamorphic processes of this age are observed in this area. Neoarchean (2750–2600 Ma) or Neoarchean–Paleoproterozoic (2550–2450 Ma) processes are also widely distributed: Vestfold Oasis, Enderby Land, Denman Glacier, where syntectonic orthogneisses and granulite facies metamorphic rocks are known.

Periods of intense Proterozoic tectogenesis may be distinguished in the intervals of 2200–2000, 1850–1700, 1400–1250, 1200–920, and 600–500 Ma. In the Lambert terrain in the Prince Charles Mountains, Adelie Land, Miller Range, and the Shackleton Range, orogenic processes (plastic deformations, metamorphism, and granite formation) took place in this period. Paleoproterozoic orogenic processes are clearly manifested in the central and eastern sectors of Atlantic shield (east of Lambert Glacier) and in the shield portion adjoining the Ross fold system of the Transantarctic Mountains. At some areas (Adelie Land) tectonic activity was completed to the boundary of 1700 Ma, but for others (for example, Lambert terrain in Prince Charles Mountains) tectonic activization took place later.

The western sector of the shield largely consists of Mesoproterozoic rocks, but at some localities evidence of inherited Archean or Paleoproterozoic material is found (Kemp Land, partly Rayner province of Enderby Land, Rauer Islands). Rocks of the majority of Mesoproterozoic complexes are thought to have originated from the intracrustal substratum and only at some areas (Fisher terrain in Prince Charles Mountains, localities at the west of Queen Maud Land, Ser-Rondane Mountains, and Bunger Oasis) juvenile matter may play a significant role [30]. On most of the Proterozoic mobile belt the Sm–Nd model age (DMT) of the primary material of the earth's crust is usually Paleoproterozoic.

Mesoproterozoic tectogenesis was not synchronous. The most active magmatic and tectonic processes took place at 1300–1100 and 1050–959 Ma (Prince Charles Mountains), 1150–1050 Ma (Queen Maud Land), 1100–920 Ma (Kemp Land, Princess Elisabeth Land), 1200–1150 Ma (Bunger Oasis area), and 1400–1135 Ma (Windmill Islands). The major stage of tectonic activity in different areas is defined at about 1150 Ma (Windmill Islands—Banger Oasis), 1050 Ma (Queen Maud Land), and 980–920 Ma (Prince Charles Mountains—Kemp Coast—Enderby Land).

Three regions may be recognized as areas of Mesoproterozoic tectogenesis: the provinces of Wilkes, Maud, and Rayner (Fig. 3). Probably, during this stage a vast continental block was gradually formed (amalgamated); according to some models, it belonged to the paleocontinent Rodinia. Possibly, this block existed during the Neoproterozoic–Paleozoic and may be correlated to Eastern Gondwana. The Early Precambrian blocks on some areas experienced thermal and magmatic activization (with granitoids and mafic dykes intruded). At a few other places (Kemp Land, west of Enderby Land, Rauer Islands) they underwent stronger tectonic and magmatic reworking with formation of folds, planar structures, and rock recrystallization.

It is thought that Late Paleoproterozoic and Mesoproterozoic tectonic and thermal events involved vast areas of the eastern sector of the Antarctic shield, including inland ice-covered areas. Evidences of endogene processes in these stages have been discovered near the inland subglacial Lake Vostok.

Neoproterozoic–Early Paleozoic tectogenesis (metamorphism, plastic deformations and granitoids intrusions) were practically simultaneous and have been dated to the interval of 550–500 Ma (up to 480–460 Ma in the area of Lambert Glacier–Mirnyi Station, where this age refers to post-tectonic granitoids). The characteristic feature of most of the Antarctic shield is high-temperature metamorphism, as well as the significant partial melting of the material of the earth's crust 550–510 Ma ago. Late Proterozoic–Cambrian processes—deep metamorphism, granite formation, and plastic deformation with pervasive schistosity—were very active in the centre of Queen Maud Land, at the west of Enderby Land (the coast of the Lutzow-Holm Bay), and on Princess Elizabeth Land (the coast of Prydz Bay, Grove Mountains, Fig. 5). A weak thermal event, or intrusion of granitoid complexes (largely veins), took place in some other sectors of Antarctic shield (Mac Robertson Land and Prince Charles Mountains, most of Enderby Land, and the Denman Glacier area). Areas on the extreme west of Queen Maud Land, and on Adelie Land, where these processes are not known to have occurred, are the exception. Therefore, tectonic events were very active during this stage.

The Late Neoproterozoic–Early Paleozoic processes on the Antarctic shield are usually called Pan-African [37] in spite of the fact that they are significantly younger than tectogenesis in Eastern Africa (up to 800 Ma [28]). The younger tectogenesis phases (570–490 Ma) intensely manifested in the southern part of Mozambique belt, in southern India and the south of Madagascar, are recognized as the so-called Kuunga orogeny. The above presented ages of endogene processes in the Eastern Antarctica suggest their correlation with the Kuunga stage.

It's worth noting that the original ideas on the exclusively thermal character of the Vendian–Cambrian processes based on K–Ar data [3] have significantly changed in the last years. This period is peculiar for practically simultaneous processes: intense intracrustal melting, evolution of a geodynamic P–T regime following a flowsheet close to isothermal decompression, and local formation of high-temperature or high-pressure metamorphism [19]. Possibly, these processes resulted from intense heat flow supplied to the over-deepened crust. The thermal evolution of these areas may be described by a model supposing collision of the continental mass and subsequent delamination of the lithosphere with the intrusion of a hot mantle mass into the base of the crust. However, the absence of juvenile rocks of this age formed under convergence geodynamic conditions gives reason to believe that the Neoproterozoic–Early Paleozoic tectogenesis was of an intra-plate nature and may have been the result of convergence orogenic processes taking place at the north of the Mozambique belt and along the Antarctica margin in the zone transitional to the Paleo-Pacific basin.

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